Chapter 10
Comparisons Between Air and Subsurface Temperatures in Taiwan for the Past Century: A Global Warming Perspective

Chieh-Hung Chen, Chung-Ho Wang, Deng-Lung Chen, Yang-Yi Sun, Jann-Yenq Liu, Ta-Kang Yeh, Horng-Yuan Yen, and Shu-Hao Chang

Abstract Air and sea surface temperature increases due to global warming have been widely observed around the world at various rates. This temperature rising has also been documented in many subsurface records recently. The air-ground temperature coupling system introduces an important factor in disturbing the original thermal balance and provides a new dimension to comprehend the effects of global warming on the Earth system. Ten meteorological stations of Central Weather Bureau in Taiwan that have been routinely measured for air (1.5 m above the ground) and subsurface (at depths of 0, 5, 10, 20, 30, 50, 100, 200, 300 and 500 cm below the ground) temperatures are used for in-depth comparison in this study. These stations have a mean observation period of 82 years (as of 2008) to provide good coverage for a preliminary examination of air-ground temperature coupling relationship in a century

C.-H. Chen (✉), C.-H. Wang, and S.-H. Chang
Institute of Earth Sciences, Academia Sinica, 128, Sec. 2, Academia Rd.,
Nangang, Taipei 11529, Taiwan, ROC
e-mail: nononochchen@gmail.com

D.-L. Chen
Penghu Station, Central Weather Bureau, 2, Xinxing Rd., Magong, Penghu 88042, Taiwan, ROC

Y.-Y. Sun
Institute of Space Science, National Central University, 300, Jhongda Rd.,
Jhongli, Taoyuan 32001, Taiwan, ROC

J.-Y. Liu
Institute of Space Science, National Central University, 300, Jhongda Rd.,
Jhongli, Taoyuan 32001, Taiwan, ROC
and
Center for Space and Remote Sensing Research, National Central University,
300, Jhongda Rd., Jhongli, Taoyuan 32001, Taiwan, ROC

T.-K. Yeh
Institute of Geomatics and Disaster Prevention Technology, Ching Yun University,
229, Jianxing Rd., Jhongli, Taoyuan 32097, Taiwan, ROC

H.-Y. Yen
Institute of Geophysics, National Central University, 300, Jhongda Rd.,
Jhongli, Taoyuan 32001, Taiwan, ROC

M. Taniguchi (ed.), *Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities*, DOI 10.1007/978-4-431-53904-9_10, © Springer 2011

scale. Results show that patterns and variations of air and subsurface temperature are quite different among stations in Taiwan. In general, air and subsurface temperatures exhibit consistent linear trends after 1980 due to accelerating global warming, but display complex and inconsistent tendencies before 1980. When surface air temperature is subtracted from subsurface one, the differences in the eastern Taiwan are generally larger than those in the western Taiwan. This observation is possibly caused by (1) heat absorption of dense high-rise buildings, and/or (2) cut off heat propagating into deep depths in the urban area of western Taiwan. By comparing temperature peaks at various layers from shallow to deep, rates of thermal propagation can be estimated. The distinct time shifts among stations suggest that thermal propagations have to be taken into account when constructing historical temperature records.

10.1 Introduction

Concentration increase of greenhouse gases in the atmosphere is generally regarded as the main cause of the global warming (IPCC 2007). Productions and surface emissions of greenhouse gases through biogeochemical processes in soil are closely modulated by air temperature (Lloyd and Taylor 1994; Risk et al. 2002a, b; Luo et al. 2001). Therefore, study of the air-ground temperature coupling is very important for climate change research (Beltrami and Kellman 2003). Many studies indicated that historical changes for ground surface temperature (GST; i.e., relatively shallow subsurface temperature) over a large range of spatial and temporal scales can be reconstructed by current measurements for temperature-depth profiles (Pollack and Huang 2000; Huang et al. 2000; Beltrami 2001a). The reconstructions are generally used to compare with historical surface air temperature (SAT) and good agreements have given credence to the relationship between SAT and GST (Huang et al. 2000; Harris and Chapman 2001; Beltrami 2002). However, the reconstructions, which have been comprised by underground temperatures at deep depths, present smoothed versions for GST history, signals such as diurnal and/or seasonal cycles would be generally lost due to a lack of short temporal variations. To evaluate causes of short-term changes in subsurface temperature, climatic variations, such as snow cover, soil freezing, evapotranspiration, and vegetations, can be well linked to GST with a good correlation if data sets are available (Baker and Ruschy 1993; Putnam and Chapman 1996; Beltrami 2001b; Zhang et al. 2001; Baker and Baker 2002; Smerdon et al. 2003, 2006).

In short, variations of subsurface temperature are mainly comprised by responses of solar radiation from the space to Earth, thermal conduction from inner Earth outward to the surface, and climatic effects near the Earth surface. Because of a long propagation distance that passed strata as a low-pass filter, the inward radiation and outward thermal conduction dominate the long-term changes of subsurface temperature. Over last decades, global warming has significantly shown on the rising trend of SAT on earth surface (IPCC 2007). This additional element enforces significant changes on the complex air-ground temperature coupling system, and sheds more lights on the relationship between GST and SAT.

Because the influence of environmental changes may sustain for a long temporal period, data recorded covering a few decades are often insufficient for long-term analyses. In this study, ten meteorological stations in Taiwan (Table 10.1) with an average observation period of 82.2 years for GST records are selected. For simplification, we compare linear trends of SAT with those of GST to study effects caused by the inward source. Meanwhile, we compute the annual changes between GST and SAT to comprehend the characteristics at each site, and further evaluate the propagation time for thermal conduction from shallow to deep depth in Taiwan.

10.2 Data

For the observation practice, sporadic measurements of GST and SAT in Taiwan could be traced to the late Ching Dynasty of China. In 1896, Taiwan Island was transferred to Japan; meteorological stations were gradually established one by one under Japanese governance and officially started the systematic observation. After 1945, Taiwan was back to the jurisdiction of Republic of China, the Central Weather Bureau (CWB) took over existing stations and expanded more for continuous observation. Till to 2008, observed periods of ten selected stations range from 41 years in Chiayi to 109 years in Hengchun. Hence, temperature records with such a long observation period are unique and valuable. In addition, these stations are distributed rather evenly in Taiwan. Taking the Taipei station as a reference, GST observation was initiated in this site of northern Taiwan from 1930 (Fig. 10.1 and Table 10.1). From the north to south, stations Hsinchu, Taichung, Chiayi and Tainan are positioned in western side, and stations Ilan, Hualien and Taitung are situated in the eastern Taiwan, respectively (Fig. 10.1). At the southern tip of Taiwan locates the Hengchun station (starting in 1900) with a typical tropics climate.

On the other hand, intense interaction between the Philippine Sea plate and the Eurasian plate results the complex topography in Taiwan and raises the Central Range up to an elevation of approximately 4,000 m (Ho 1988). Station Jiyuehtan was built in the central Taiwan with the altitude of about 800 m and experiences much less influence of human activity. In terms of geology, these stations are all set on the Quaternary sediment resulting from intensity erosion of Tertiary strata in high altitudes (Ho 1988). Because the observation depth is confined to a depth within 5 m from surface, geological background is very similar for all stations. In short, temperature changes under the distinct climate regions (subtropics vs. tropics), different altitudes, urban and rural environments can be evaluated by comparing records in these stations.

GST and SAT records generate a good contrast within one site between these two observation data sets. SAT is recorded with a high sampling interval of 1 min at a height of 1.5 m above the surface. On the other hand, GST data are obtained once a day at depths of 0, 5, 10, 20, 30, 50, 100, 200, 300 and 500 cm (Table 10.1). For a long observation, data continuity is very important and has to be taken into account. In this work, ten observation depths in the ten stations would yield 100 GST data series, 61 of them have the percentages larger than 99%, especially at

Table 10.1 Location, observation periods (year) and data continuity (%) in the stations. Note that the year shown in Table 10.1 is a comprehensive result from entire subsurface observation depths. The percentages of the data continuity are computed using the observation periods at each depth

Stations	Long.	Lat.	Periods	0 cm	5 cm	10 cm	20 cm	30 cm	50 cm	100 cm	200 cm	300 cm	500 cm
Taipei	121.51	25.04	1930–1996	99.4	99.6	99.4	99.4	72.6	99.6	99.6	99.5	97.2	91.0
Hsinchu	121.01	24.83	1939–	100.0	100.0	99.9	100.0	100.0	100.0	100.0	100.0	99.7	99.6
Taichung	120.68	24.15	1901–	99.5	99.9	93.9	89.4	85.9	99.9	99.9	100.0	99.9	88.4
Jiyuehtan	120.9	23.88	1950–	98.8	98.8	98.8	92.2	98.3	98.9	98.9	98.9	98.0	98.0
Chiayi	120.42	23.5	1968–	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9
Tainan	120.2	23	1900–2001	99.9	99.8	95.3	89.7	88.2	96.0	96.0	100.0	96.0	92.7
Hengchun	120.74	22.01	1900–	98.6	98.3	96.8	74.4	72.6	99.4	99.4	99.2	99.4	99.2
Taitung	121.15	22.75	1902–	100.0	100.0	100.0	100.0	100.0	99.9	98.0	100.0	96.4	97.2
Hualien	121.61	23.98	1922–	100.0	99.9	99.9	99.9	99.8	99.8	99.2	99.9	99.9	100.0
Ilan	121.75	24.77	1936–	99.3	99.9	100.0	98.8	97.8	83.1	83.1	82.6	82.6	83.1

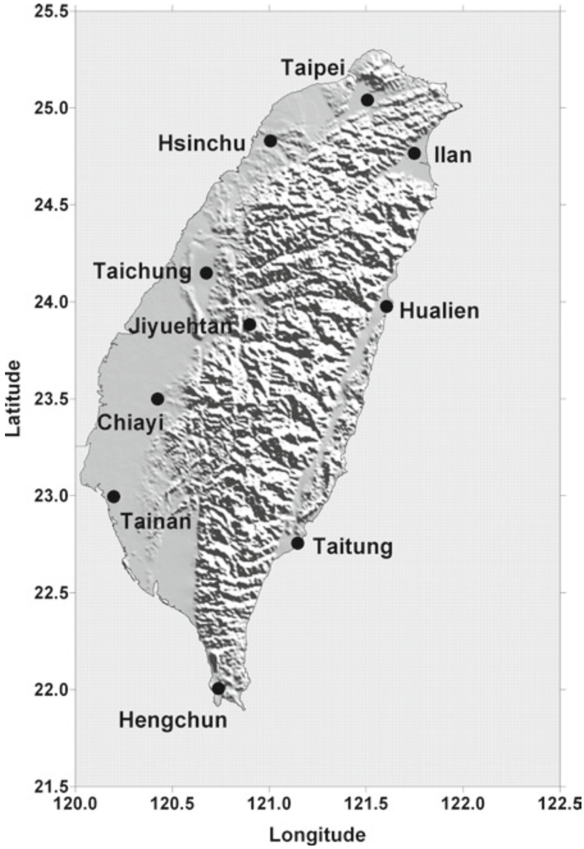

Fig. 10.1 Locations of subsurface temperature stations denoted by *circles*

stations of Hsinchu, Chiayi and Hualien (Table 10.1). In other words, mean data gaps are less than 3 days in 1 year at most stations. In contrast, only 13 data series are smaller than 90% and mainly found in the Ilan station (Table 10.1).

For a better comparison, both minute measurements for SAT and daily records for GST are integrated into mean-annual temperatures. Station Hualien is taken as an example to describe temperature changes in the long temporal domain. Figure 10.2 shows linear trends of the mean GST and SAT at the Hualien station using the least square method (Rao et al. 1999; Wolberg 2005) to examine their relationships. The mean-annual SAT at Hualien ranged between 21.5°C and 24°C from 1922 to 2008, and shows a clear upward trend of 0.14°C/10 year (Fig. 10.2a). On contrast, the mean-annual GST at depth 0 cm displays scattering distribution and reveals an unclear tendency during the entire 87 years (Fig. 10.2b). For the depth of 5 cm, the temperature variations fitted with a linear trend are apparently inappropriate because two discrete patterns are clearly found before and after 1980 (Fig. 10.2c). This suggests a turning point may be in existence approximately in 1980. Regarding the subsurface temperature at depth of 10 cm, data are consistent to a fitting trend of 0.17°C/10 year. In terms of the deeper depths, patterns of the

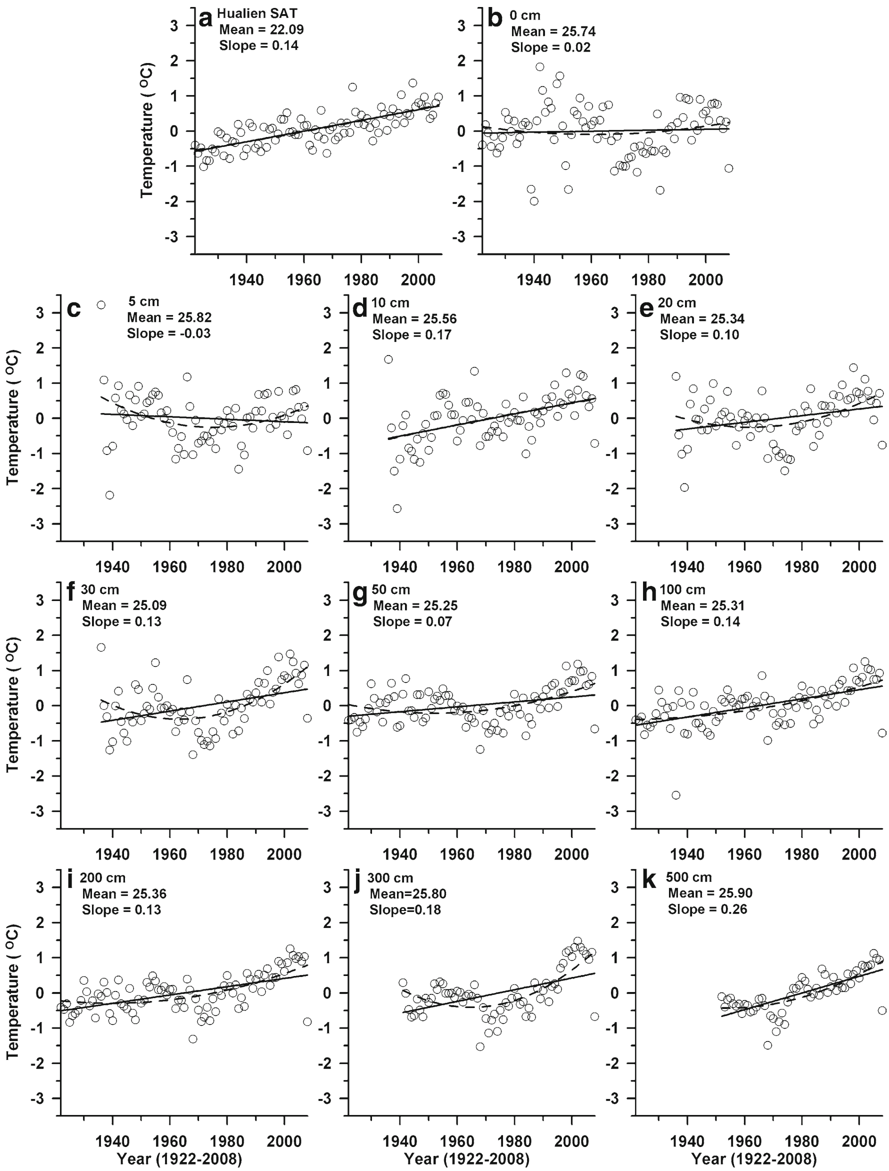

Fig. 10.2 Variations of yearly mean subsurface and SAT at the Hualien station from 1922 to 2008. (**a**) SAT variations; (**b**)–(**k**) subsurface temperatures at depths of 0, 5, 10, 20, 30, 50, 100, 200, 300 and 500 cm, respectively. The *open circles* show the yearly mean temperature and are expressed as departures from long-term means. *Solid lines* and *dashed curves* denote tendencies of yearly mean temperature using the linear trends and second-order functions, respectively. Note that the slop (°C/10 year) indicates the long-term trend of temperature changes within study periods

subsurface temperatures at depths of 20, 30, 50, 100, 200, 300 and 500 cm are roughly similar with that at 5 cm depth, showing that distinctively negative and positive slopes dominate the temperature changes before and after 1980 respectively (Fig. 10.2e–k). In short, the negative tendencies are generally observed before 1980 at deep depths and positive trends found after 1980 at most depths.

Because the year 1980 seems to be a key turning point with respect to environmental change, linear trends of GST and SAT records before and after 1980 are computed to further understand temperature transformations that may be possibly induced by the effect of global warming (Table 10.2). Table 10.2 exhibits statistical results for the linear trends before and after 1980 for ten stations. The increase or decrease trends are regarded as significant when the slopes ≥0.1°C/10 year or ≤−0.1°C/10 year, respectively. SATs at nine stations have conspicuous increasing tendencies after 1980. It is worth to mention that the decrease tendencies are found during the entire observation period only at the Jiyuehtan station. Regarding the subsurface temperature before 1980, the prominent increase trends are only observed at stations with a proportion between 0% and 30%. In contrast, 30% to 63% stations show evident increase trends after 1980. Meanwhile, tendencies before 1980 were subtracted from those after 1980 to study temperature trend shifts. Similarly, difference of the slopes being larger (or smaller) than 0.1°C/10 year (or −0.1°C/10 year) is determined as significant changes. For SAT, the prominent positive changes are found in most stations, except for stations Jiyuehtan and Chiayi. In a comprehensive survey, the GST and SAT do present strong positive transformations possibly due to the effect of global warming, but these features show inconsistencies in trends for stations of Taipei and Hengchun.

To examine this inconsistent relationship, monthly distributions of long-term subsurface temperatures for various depths (0–500 cm) (MSTs) and for SAT (MAT) are computed respectively. Data of each month are averages of the entire observation period. Here, the Taipei station is taken as an example to understand the relationship between MST and MAT (Fig. 10.3). Figure 10.3a illustrates that MAT is distributed between 15°C and 29°C in this metropolitan station. With the increase of depths, the distribution ranges of MST are sharply reduced down to between 22°C and 24°C at the depth of 500 cm. It is interesting to find that the phases of MST are also correlated with the observation depth. The highest and lowest temperatures observed at shallow levels are gradually departed from July and January through depths, respectively. The time shift of the phase changes between the surface and the depth of 500 cm is about 4 months in Taipei. Moreover, Fig. 10.3b shows the difference given by subtracting MST from MAT at each depth for the Taipei station. The similar patterns between MAT and MST at the shallow depths (≤10 cm) yield a small residual value with an average about 0.5°C and are varied within a small range of ±0.5°C (Fig. 10.3a). The obtained ranges increase with the observation depth of MST and reaches to ±7.5°C for the deepest measurement (500 cm), which is one order magnitude larger than that of the shallow depth (±0.5°C).

Figures 10.4 and 10.5 present the averages and ranges of the differences (MST-MAT) at the shallow (≤10 cm) and deep (≥100 cm) depths respectively, corresponding

Table 10.2 The linear trends (°C/10 years) before and after 1980 and their statistic results at each depth in the stations. Here, D% and I% denote proportions of the stations with decrease and increase transformations of the trends before and after 1980, respectively. Note that T% indicates the percentages of the stations with an increase trends >0.1°C/10 years of subsurface and SAT during the associated period

	SAT		0 cm		5 cm		10 cm		20 cm		30 cm		50 cm		100 cm		200 cm		300 cm		500 cm		Each station	
Stations	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	1900–1980	1980–2008	D%	I%
Taipei	0.115	0.402	−0.269	−0.109	−0.138	−0.475	−0.247	−0.437	−0.262	−0.252	−0.263	−0.418	−0.187	−0.707	−0.153	−0.581	−0.092	−0.733	−0.101	−0.217	−0.112	−0.090	80%	0%
Hsinchu	0.071	0.289	−0.562	0.051	−0.261	0.014	−0.322	0.125	−0.334	0.049	−0.177	−0.018	0.168	0.285	0.040	0.230	0.049	0.051	0.151	0.189	0.188	0.269	0%	70%
Taichung	0.119	0.438	−0.055	0.139	−0.227	−0.161	−0.195	−0.030	−0.125	−0.022	−0.062	−0.211	0.073	−0.064	0.049	0.026	0.064	0.198	0.047	0.250	0.254	0.308	20%	50%
Jiyuehtan	−0.067	−0.059	−0.276	−0.216	−0.541	−0.103	−0.262	−0.313	−0.104	−0.218	0.067	−0.289	−0.189	−0.137	−0.083	−0.093	−0.103	−0.091					27%	27%
Chiayi	0.697	0.352	0.367	0.116	0.445	0.031	0.548	0.090	0.453	0.164	0.033	−0.025	0.279	0.053	0.172	0.144	−0.268	0.261	−0.444	0.222	−0.446	0.128	50%	30%
Tainan	0.172	0.382	−0.147	0.087	0.082	0.019	0.026	0.215	0.288	−0.090	0.087	0.272											0%	30%
Hengchun	0.132	0.232	0.066	−0.371	0.080	−0.129	0.144	−0.276	0.011	−0.130	−0.030	−0.278	0.090	−0.115	0.137	0.034	0.066	0.065	0.050	0.043	0.153	0.092	70%	0
Taitung	0.119	0.247	−0.301	0.236	0.256	0.196	−0.142	0.160	0.001	0.045	−0.047	0.141	−0.007	0.067	−0.051	−0.244	−0.099	−0.032	0.007	−0.082	0.080	−0.043	10%	30%
Hualien	0.135	0.265	−0.087	0.293	−0.224	0.167	0.164	0.281	−0.150	0.176	−0.130	0.470	−0.040	0.343	0.087	0.267	0.028	0.293	−0.104	0.564	0.054	0.217	0%	100%
Ilan	0.082	0.323	−0.271	0.141	0.049	0.530	0.072	0.405	0.067	0.373	0.194	0.368	0.004	0.434	0.007	0.399	0.054	0.256	0.032	0.542	−0.047	0.466	0%	100%
T%	70%	90%	10%	50%	20%	30%	30%	50%	20%	30%	10%	40%	22%	33%	22%	44%	0%	44%	13%	63%	27%	63%	0%	100%

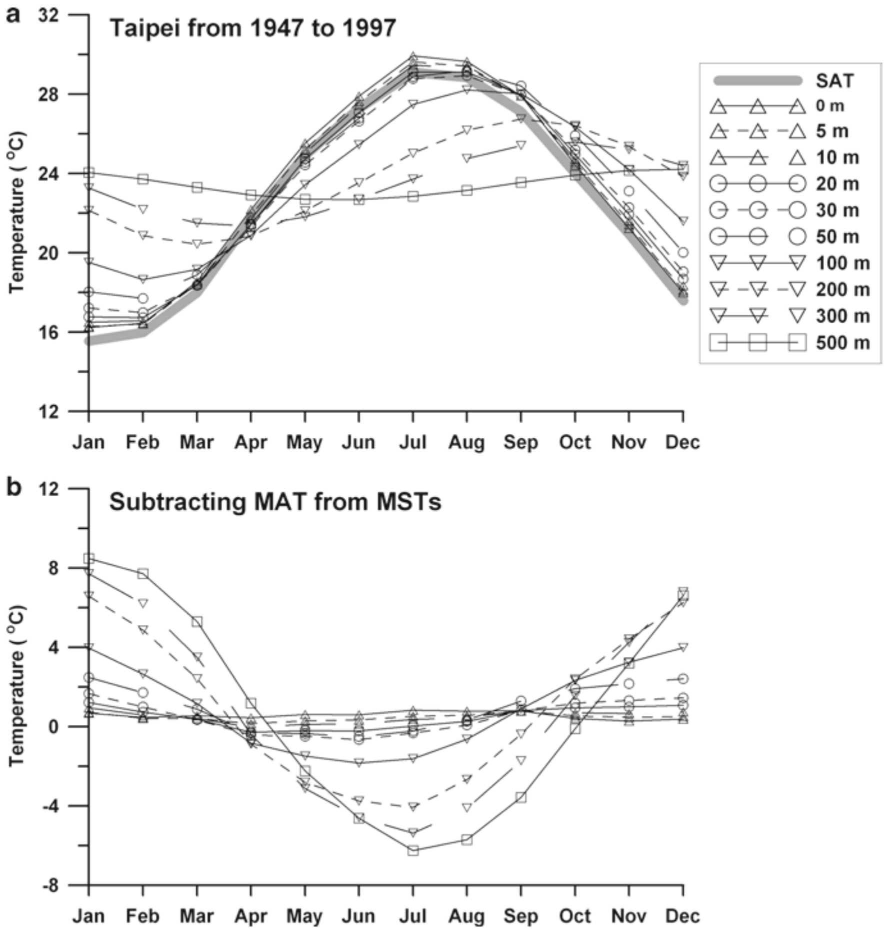

Fig. 10.3 Monthly distributions of long-term subsurface temperatures for various depths (0–500 cm) (MSTs) and MAT, and the patterns of their difference. MSTs and MAT given by averages of the entire observation period of data in each month are shown in (**a**). The patterns of MAT subtracting from MSTs are displayed in (**b**)

to their latitudes. The averages and ranges of the differences at the shallow depths are both inversely proportional to the latitude (Fig. 10.4a, b). The positive averages mainly ranged between 0°C and 3°C clearly indicate temperature discontinuity does in existence near the Earth surface due to distinct thermal conductivity. With respect to deep depths, the averages of temperature difference gradually decrease with the higher latitude, and are in good agreement with those in shallow depths (Fig. 10.5a). The ranges of the difference, which are proportional to the latitude, imply that impacts of SAT are sharply reduced with depths (Fig. 10.5b). Furthermore, the difference range of the Jiyuehtan station with a relative high

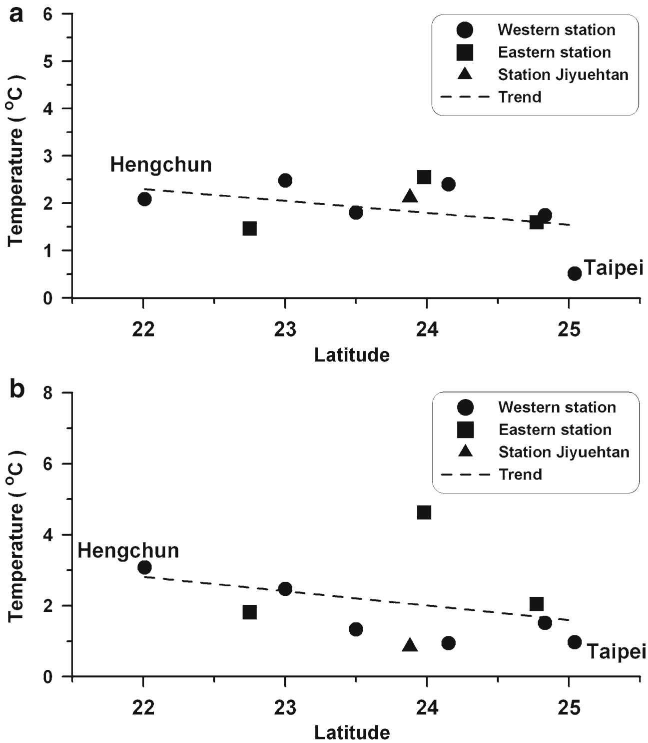

Fig. 10.4 Relationship between the averages and ranges of the differences (MSTs-MAT) at the shallow depths (<10 cm) with latitudes. Averages and ranges of the differences are shown in (**a**) and (**b**), respectively. *Circles* denote the stations located in the western Taiwan. In contrast, *squares* indicate the stations located in the eastern Taiwan. Station Jiyuehtan with the relative high altitude is marked by *triangle symbols*. Note that the *dashed lines* show the linear trends of the relationship

altitude is significantly smaller than those of other stations of similar latitude due to small variations of MAT. By comparing the stations with similar latitudes (Hsinchu V.S. Ilan, Taichung V.S. Hualien and Tainan V.S. Taitung), it is interesting to note that the difference ranges of the western stations are generally larger than those of the eastern stations with a range of about 1–3°C.

To study the departing of extreme temperatures of July and January relative to depth, the subsurface temperature at 0 cm were taken as a reference to estimate the time shift for each observation depth using the cross correlation method (Campbell et al. 1997). The time shifts of temperature at each depth relative to surface in all stations are listed in Table 10.3, and the relationships of the Hualien and Ilan stations are shown in Fig. 10.6 in parallel. The time shifts are shorter than 3 days at all stations with a depth shallower than 50 cm (Table 10.3 and Fig. 10.6). When the

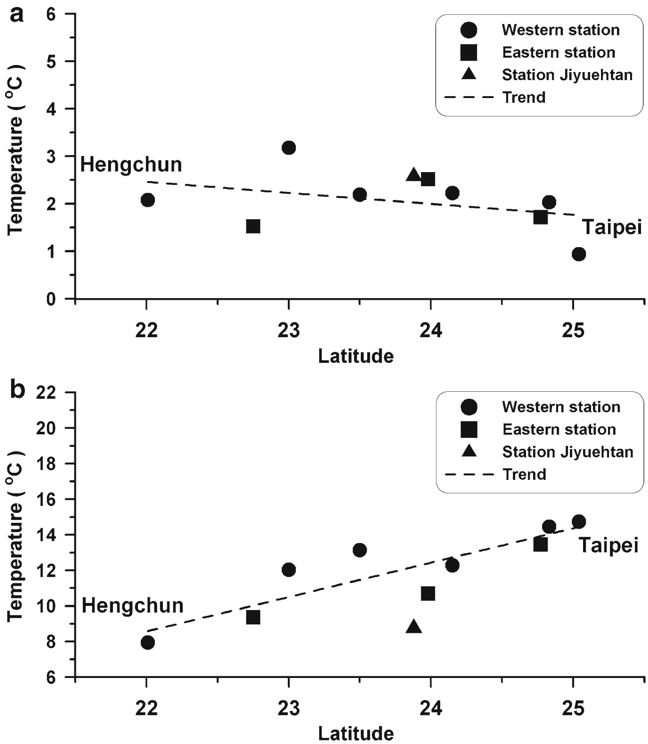

Fig. 10.5 Relationship between the averages and ranges of the differences (MSTs-MAT) at the deep depths (>100 cm) with latitudes. Averages and ranges of the differences are shown in (**a**) and (**b**), respectively. *Circles* denote the stations located in the western Taiwan. In contrast, *squares* indicate the stations located in the eastern Taiwan. Station Jiyuehtan with relative high altitude is marked by *triangle symbols*. *Dashed lines* show the linear trends of the relationship

Table 10.3 The time shifts relative to peaks of ground surface temperature each depth in the stations (unit: day)

Station	5 cm	10 cm	20 cm	30 cm	50 cm	100 cm	200 cm	300 cm	500 cm
Taipei	1	1	2	2	3	21	52.5	74.5	134
Hsinchu	1	1	2	2	3	15	41	53.5	91
Taichung	1	1	2	2	3	12	40	58	83
Jiyuehtan	1	1	2	2	3	18.5	43	54	82
Chiayi	1	1	2	2	3	23	45	72	120
Tainan	1	1	2	2	2	13	47	68.5	104
Hengchun	1	1	2	2	3	7	43.5	69	116.5
Taitung	1	1	2	2	2	5	42	55	85
Hualien	1	1	1.5	2	3	5	29	48	85
Ilan	1	1	2	2	2	18	44	70	120

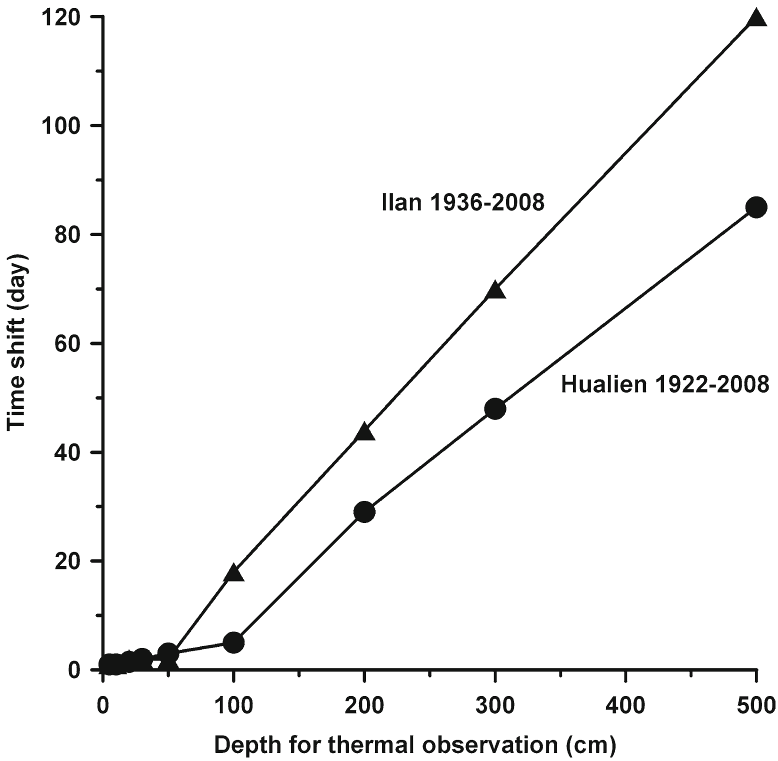

Fig. 10.6 Relationship between time shifts with various depths. Lines with *triangles* and *circles* denote the relationships in Ilian and Huanlien, respectively

depth gets deeper than 100 cm, the time shifts apparently increase with a linear trend and reach 82–134 days at the 500 cm depth (Table 10.3).

10.3 Discussion and Conclusions

The time shifts from 0 to 500 cm can be separated into three groups (Table 10.3). The short time shift (82–85 days) at the Jiyuehtan, Taichung, Taitung and Hualien stations infers that relatively high efficient geothermal conductivity is mainly distributed in the eastern part of Taiwan and extends to the western side of central Taiwan. Stations Hsinchu and Tainan with the medium time shift (91 and 104 days, respectively) are located at two transitional zones. Two end-member areas, which are either north or south from Hsinchu and Tainan, appear to have the longer time shift (116.5–134 days). The long time shift suggests that heat takes much time for propagating from the shallow to deep depth at the Hengchun, Chiayi, Ilan and Taipei stations. The variations of time shifts among stations indicate that the geothermal conductivity is an important factor even if temperature history is reconstructed in a small region.

Stations with long temporal periods and evenly distribution in Taiwan generate good temperature records to study the relationship between GST and SAT for various environment conditions. High SAT with small variations is observed in the low latitude and tropical climate. On contrast, low SAT with large variations is recorded in the high latitude. Figure 10.4 shows the ranges and averages of the differences between MST and MAT of shallow depths are both inversely proportional to the latitudes. For stations that are located in the low latitude with high SAT, temperature yields large differences between surface and subsurface records. In terms of the deep depths, the ranges of the difference (MST-MAT) are increased with higher latitudes (Fig. 10.5b). This implies that depth effect of high SAT is smaller than those of low SAT. Thus, the depth effect needs to be taken into account during temperature reconstructions processes.

For site comparison, the yearly mean of SAT presents an increase trend along with global warming and is consistent with most areas in the world. On the other hand, the subsurface temperature with decrease trends is observed at most depths in Taipei (Table 10.2). A further comparison of the linear trends of similar latitude stations (Hsinchu V.S. Ilan, Taichung V.S. Hualien and Tainan V.S. Taitung), it is clear to note that the temperature increase rate in eastern Taiwan is higher than it in the western part (Table 10.2). Because urban cities and rural sections can be roughly separated into the western and eastern sides of Taiwan, subsurface temperature with the small increase rates in the western side suggesting that high-rise buildings possibly cut off and/or absorb the inward thermal propagation and take hold of heat on the Earth surface, especially the holistic negative trends in metropolitan Taipei because Taipei has been the rapidest and most extensive developing area in Taiwan (Chen et al. 2007). These features imply that global warming signals may be underestimated due to contributions from negative feedbacks.

Furthermore, Table 10.2 exhibits that SAT generally has an increase trend during the entire observation period. However, subsurface temperatures with positive or negative changes can be found at various depths after 1980, but this feature is mainly confined in shallow depths before 1980. This suggests that the original patterns of GST and SAT are certainly different. In addition, the significant positive transformations before and after 1980 are widely observed both in subsurface and SAT in Taiwan. Therefore, a high correlation between GST and SAT should be dominated by the similar responses resulted from same impact sources. Temperature changes at different layers are roughly consistent among most stations. The temperature reconstructions should be generated using consistent transformation changes, correlated with the long-term trends at each depth and simultaneously take the time shift with depth into account. Meanwhile, global warming has persistently affected the subsurface temperature to generate significant positive changes on the trends after 1980. This is a serious warning that the persistent warming environments are not only affect the air and water domains, but also gradually extend to soil, rocks of the Earth’s lithosphere.

References

Baker JM, Baker DG (2002) Long-term ground heat flux and heat storage at a mid-latitude site. Clim Change 54:295–303

Baker DG, Ruschy DL (1993) The recent warming in eastern Minnesota shown by ground temperatures. Geophys Res Lett 20:371–374

Beltrami H (2001a) Surface heat flux histories from geothermal data: inference from inversion. Geophys Res Lett 28:655–658

Beltrami H (2001b) On the relationship between ground temperature histories and meteorological records: a report on the Pomquet station. Glob Planet Change 29:327–352

Beltrami H (2002) Climate from borehole data: energy fluxes and temperatures since 1500. Geophys Res Lett. doi:10.1029/2002GL015702

Beltrami H, Kellman L (2003) An examination of short- and long-term air–ground temperature coupling. Glob Planet Change 38:291–303

Campbell JY, Lo A, MacKinlay AC (1997) The econometrics of financial markets. Princeton University Press, Princeton

Chen TC, Wang SY, Yen MC (2007) Enhancement of afternoon thunderstorm activity by urbanization in a valley: Taipei. J Appl Meteorol Climat 46:1324–1340

Harris RN, Chapman DS (2001) Mid latitude (30 deg – 60degN) climatic warming inferred by combining borehole temperature with surface air temperature. Geophys Res Lett 28:747–750

Ho CS (1988) An introduction to the geology of Taiwan, 2nd edn. Central Geological Survey, The Ministry of Economic Affairs, Taipei

Huang S, Pollack HN, Shen PY (2000) Temperature trends over the last five centuries reconstructed from borehole temperatures. Nature 403:756–758

IPCC (2007) Climate change 2007: the physical science basis – summary for policymakers, intergovernmental panel on climate change, Geneva, IPCC WGI 4th Assessment Report

Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. Funct Ecol 8:315–323

Luo Y, Wan S, Hui D, Wallace L (2001) Acclimatization of soil respiration to warming in a tall grass prairie. Nature 413:622–625

Pollack HN, Huang S (2000) Climate reconstructions from subsurface temperatures. Annu Rev Earth Planet Sci 28:339–365

Putnam SN, Chapman DS (1996) A geothermal climate change observatory: first tear results from Emigrant Pass in northwest Utah. J Geophys Res 101:21877–21890

Rao CR, Toutenburg H, Fieger A, Heumann C, Nittner T, Scheid S (1999) Linear models: least squares and alternatives, 2nd edn. Springer Verlag, Berlin, Heidelberg, New York (Springer Series in Statistics)

Risk D, Kellman L, Beltrami H (2002a) Carbon dioxide in soil profiles: production and temperature dependence. Geophys Res Lett. doi:10.1029/2001GL014002

Risk D, Kellman L, Beltrami H (2002b) Soil CO_2 production and surface flux at four climate observatories in eastern Canada. Glob Biogeochem Cycles. doi:10.1029/2001GB001831

Smerdon JE, Pollack HN, Enz JW, Lewis MJ (2003) Conduction-dominated heat transport of the annual temperature signal in soil. J Geophys Res. doi:10.1029/2002JB002351

Smerdon JE, Pollack HN, Cermak V, Enz JW, Kresl M, Safanda J, Wehmiller JF (2006) Daily, seasonal and annual relationships between air and surface temperatures. J Geophys Res. doi:10.1029/2004JD005578

Wolberg J (2005) Data analysis using the method of least squares: extracting the most information from experiments. Springer Verlag, Berlin, Heidelberg, New York

Zhang T, Barry RG, Gilichinsky D, Bykhovets SS, Sorokovikov VA, Ye JP (2001) Am amplified signal of climatic change in soil temperatures during the last century at Irkutsk, Russia. Clim Change 49:41–76